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New evidence for the reawakening of Teide volcano

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Abstract

Geophysical signals accompanying the reactivation of a volcano after a period of quiescence must be evaluated as potential precursors to impending eruption. Here we report on the reactivation of the central volcanic complex of Tenerife, Spain, in spring 2004 and present gravity change maps constructed by time-lapse microgravity measurements taken between May 2004 and July 2005. The gravity changes indicate that the recent reactivation after almost a century of inactivity was accompanied by a sub-surface mass addition, yet we did not detect widespread surface deformation. We find that the causative source was evolving in space and time and infer fluid migration at depth as the most likely cause for mass increase. Our results demonstrate that, even in the absence of previous baseline data and ground deformation, microgravity measurements early in developing crises provide crucial insight into the dynamic changes beneath a volcano.

Introduction

Anomalous geophysical signals at dormant volcanoes, or those undergoing a period of quiescence, need to be evaluated as potential precursors to reawakening and possible eruption [*White*, 1996]. There are several recent examples of volcanic re-activation after long repose intervals culminating in explosive eruption [*Nakada and Fuji, 1993; Robertson et al., 2000*], but non-eruptive behaviour is equally documented [*De Natale et al.*, 1991; *Newhall and Dzurisin*, 1988]. The dilemma scientists are confronted with is how to assess future behaviour and to forecast the likelihood of an eruption at a reawakening volcano, when critical geophysical data from previous activity is missing due to long repose periods. In Spring 2004, almost a century after the last eruption on the island, a significant increase in the number of seismic events located inland on the volcanic island of Tenerife (Fig. 1) marked the reawakening of the central volcanic complex (CVC), the third-highest volcanic complex on Earth rising almost 7000 m from the surrounding seafloor [*García et al.*, 2006]. The increase in onshore seismicity, including five felt earthquakes, coincided with both an increase in diffuse emission of carbon dioxide along a zone known as the Santiago Rift [*Pérez et al.*, 2005] and increased fumarolic activity at the summit of the 3718 m high Teide volcano [*García et al.*, 2006].

Integrated geodetic network on Tenerife

As a reaction to the developing crises, we installed the first joint ground deformation/microgravity network on the island in early May 2004, two weeks after the start of increased seismicity. The network consists of 14 benchmarks, which were positioned to provide coverage of a rather large area (> 500 km^2) of the CVC, including the Pico Viejo-Pico Teide complex (PV—PT), the Las Cañadas caldera (LCC) as well as the Santiago Rift (SR) (Figs. 1 and

2). The network was designed to meet rapid response requirements, i.e. the network can be fully occupied to a precision of less than 0.01 mGals of individual gravity readings and less than 0.04 m in positioning errors within 6 working days despite the frequently rugged terrain. The first reoccupation of the network was performed in July 2004, followed by campaigns in April 2005 and July 2005. Benchmark locations and cumulative ground deformation and gravity changes between May 2004 and July 2005 are given in Tables 1-4 in the supporting online material. All results are given with respect to a reference located south of the LCC (benchmark LAJA). Within the average precision of benchmark elevation measurements (± 0.03 m), using two dual-frequency GPS receivers during each campaign, we did not observe widespread ground deformation. However, between May 2004 and July 2005, four benchmarks, two located in the eastern sector of the LCC (MAJU and RAJA), one marking the northern-most end of the network and also the lowest elevation (766 m; CLV1) and finally a benchmark located on an isolated rock spur on the western LCC rim (UCAN, supporting online material) did show ground uplift above measurement precision. Residual gravity changes (corrected for the theoretical Free-Air effect), observed during the May-July 2004, May 2004-April 2005 and May 2004-July 2005 periods are listed in the supporting online material and shown in Figure 2.

Results

The observed gravity changes do not fit a simple symmetrical pattern as observed, for example, during caldera unrest at the Campi Flegrei [*Gottsmann et al.*, 2003] or at Long Valley [*Battaglia et al.*, 2003]. The spatial distribution of gravity changes across the area under investigation is asymmetrical. The smallest gravity changes were observed in the central and eastern depression of the LCC, where cumulative changes over the 14-month period where only slightly higher than the precision level (± 0.015 mGal on average; 1 mGal= 10µm/s^2). A marked positive gravity anomaly, with a maximum amplitude of around 0.04 mGal, developed in the North-West of the covered area between May and July 2004, while a negative anomaly was found to the east, centered on station MIRA. The gravity increase noted between the first two campaigns (benchmarks C774 and CLV1) was followed by a decrease sometime between July 2004 and April 2005. During the same period, a N-S trending positive anomaly appears north-west of the PV-PT summit area between, reaching the western part of the LCC (Figs. 2a-b). In addition, gravity increased significantly along the northern slopes of Pico Teide, including benchmarks TORR and FUEN located close to the La Orotava valley between July 2004 and April 2005, adding to the impression of a spatio-temporal evolution of the causative source. It is interesting to note that on 5 December 2004 a new fissure with fumarole emission appeared in the Orotava valley [*www.iter.es*]. A gas plume emanating from the summit fumaroles of Pico Teide was particularly noticeable during October 2004 [*García et al.*, 2006], between surveys 2 and 3. In summary, significant gravity changes occurred mainly across the northern flanks of the PV-PT and along a ca. 6 km wide zone along the western side of the volcanic complex into the westernmost parts of the LCC between May 2004 and July 2005 (Fig. 2c). During the same time, a marked gravity decrease was recorded at the intersection of the Orotava Valley (OV) and the LCC (Fig. 2c).

Except for two benchmarks (MAJU and RAJA) where observed gravity changes can be explained by free-air effects (gravity changes due to elevation changes), mass/density changes in the sub-surface appear to cause the major part of the perturbation of the gravity field.

The effect of water table fluctuations

Data from two drill holes, located in the eastern half of the LCC (Fig. 2d), provide information on water table fluctuations during the period of interest. A drop of ca. 5 cm/month between surveys 1 and 4 was recorded in one drill hole located close to benchmarks 3RDB and MAJU, which is similar to the average monthly drop in water level due anthropogenic extraction over the past 3 years [*Farrujia et al.*, 2004]. Water levels decreased by 22 cm/month on average between February 2000 and January 2004 in a drill hole located close to benchmark MIRA. The gravity decrease of 0.025 mGal recorded between May 2004 and July 2005 at benchmark MIRA, located at the intersection of the Las Cañadas caldera and the Orotava valley, can be explained by a net water table decrease (δh) of 3 m, consistent with this earlier trend, assuming a permeable rock void space (ϕ) of 20 % and a water density (ρ) of 1000kg/m^3 ($\Delta g_w = 2\pi G \rho \phi \delta h$) [*Battaglia et al., 2003*]. Following the same rationale, gravity changes at 3RDB and MAJU are corrected by -0.008 mGal to account for the recorded water table fall in the nearby borehole. Hence, any gravity change observed within the central and eastern parts of the LCC (3RDB, MAJU, RAJA, MIRA) can be fully attributed to changes in (shallow) groundwater levels and we treat the net mass change as zero for this area in the computation of overall mass changes in the following sections (Fig. 2d).

Outside the LCC, comprehensive monitoring data on groundwater level is lacking and correction for groundwater level variations is difficult. Groundwater is collected and extracted along several hundred (sub)horizontal tunnels (*galerias*) protruding into the upper slopes of the CVC [*Marrero et al.*, 2005]. Since 1925, a decrease of several hundred meters in the groundwater level has been noted for the area covered by the northern and western slopes of the CVC [*http://www.aguastenerife.org/*]. We therefore consider it very unlikely that the gravity increase noted in the north and west of the CVC is related to an increase in the groundwater table, and hence infer deeper processes to be the most probable cause of gravity change in this region.

Interpretation

The coincidence of earthquake epicenter concentration (a mixture of volcano-tectonic events and regional earthquakes with pure volcanic events such as tremors and long-period signals) in the area of gravity increase over the same time period (Fig. 2d), suggests that both signals are related to the same or linked phenomena. Unfortunately, precise data on earthquake hypocentres are not available, but a semi-qualitative analysis suggests a depth of several kilometres [R. *Ortiz*, personal communication]. The spatial coverage of the benchmarks does not allow the wavelength of the May 04 – July 05 gravity anomaly to be assessed precisely. In particular, the lower limit of the wavelength along the northern slopes of the PV-PT complex cannot be unambiguously retrieved on the basis of the available data. The maximum wavelength of the gravity anomaly is on the order of 17 km if defined by both observed and interpolated (kriging) data (Fig. 2d) on the northern slopes of the PV-PT complex, which implies a maximum source depth of between 2.5 to 5.2 km below the surface, assuming simple axisymmetrical source geometries [*Telford et al.*, 1990]. This would place the source to within the depth of the shallow magma reservoirs beneath the PV-PT complex believed to host chemically evolved magma [*Ablay et al.*, 1998]. However, since the positive anomaly is only defined by 4 benchmarks (CLV1, C774, CRUC and TORR) its actual wavelength could be smaller than 17 km and the source depth could be shallower than inferred above. Furthermore, ambiguities remain on the actual amplitude of the anomaly, which is defined only by data observed at CRUC.

The continuation of the positive anomaly in the western part of the LCC (Fig. 2c) shows a shorter wavelength indicating a shallow (few km deep) source.

Due to the spatial separation of benchmarks an assessment of sub-surface mass addition is greatly biased on the selection of the area affected by gravity increases. We define a maximum area by a kriging-based interpolation of the gravity changes between May 2004 and July 2005 in the northern and western parts of the CVC. A Gaussian Quadrature integration over this area gives a mass addition of $1.1 * 10^{11}$ kg, with lower and upper 95% confidence bounds of $8.4 * 10^{9}$ kg and $2.0 * 10^{11}$ kg, respectively. These values should be regarded as maximum values.

In theory, subsurface volume changes derived from ground deformation data can be correlated to sub-surface mass changes from gravity data to infer the density of the causative source. However, in the absence of significant surface deformation, the source density cannot be determined directly and the nature of the source remains ambiguous. However, three scenarios are worth considering when assessing causative processes for the observed gravity increase: i) arrival of new magma at depth, ii) migration of hydrothermal fluids and iii) a hybrid of both.

Volcanic eruptions of the CVC over the past few centuries were dominantly fed by basic and intermediate magmas in the form of fissure eruptions along the Santiago Rift [*Ablay and Marti*, 2000], implying shallow dyke emplacement along this NW-SE trending extension zone. The observed gravity increase between May 2004 and April 2005 (Fig. 2) appears to denote a zone at a 45° angle to the strike of the rift. The wavelength of the anomaly in the western and central parts of the LCC (Fig. 2d) is not consistent with shallow dyke emplacement to perhaps within a few tens or hundred meters depth. There is also no other direct geophysical or geochemical evidence in support of magma emplacement in the form of a shallow dyke over the 14 month observation time. However, dyke emplacement at greater depth (a few km below the surface) into the Santiago Rift (with partial contribution to the gravity increases at benchmarks CLAV1, C774 and CRUC), perhaps recharging an existing reservoir, cannot be unambiguously excluded for the period May-July 2004, coinciding with the peak in the number of earthquakes recorded by the National Geographic Institute [*http://www.ign.es*]. Dykes along the Santiago Rift are on average less than 1 m wide. Ground deformation caused by an individual dyke of this size a few km below the surface would be below the precision of our GPS measurements. Thus, a magma injection into a conjugated fault system, perhaps at some angle to the Santiago Rift, cannot be unambiguously ruled out as the trigger for the reawakening of the volcanic complex in May 2004. There is, however, little evidence to support the idea that the mass increase observed during campaigns 2 and 3 is caused solely by magma movement.

An alternative explanation for the observed gravity increase is fluid migration through the CVC. Volcano-tectonic events detected in the seismic record [*García et al.*, 2006, *Tárraga et al.*, 2006] may have triggered the release and upward migration of hydrothermal fluids from a deep magma reservoir. Alternatively, fluid migration may have resulted from (a) the perturbation of an existing deep hydrothermal reservoir and resultant upward movement of fluids due to magma injection or (b) from pressurising seawater saturated rocks.

Migration of hydrothermal fluids through a permeable medium causes little surface deformation, but the filling of pore space increases the bulk density of the material resulting in a gravity increase at the ground surface. To explore this scenario, and as a first order approximation, we performed a inversion of the gravity change recorded between May 2004 and July 2005 along the northern and western slopes of the PV-PT complex for a source represented by a N-S striking infinite cylindrical horizontal body [*Telford et al.*, 1990]. The approximation of an infinite body is valid as long as the radius of the cylinder is far smaller than its length. The model results depend linearly on density change but non-linearly on both the radius and depth of the body. Using a global optimization iterative method [*Sen and Stoffa*, 1995] with various initial values for depth and radius, we find convergence of the inversion results at a depth of 1990±120 m below the surface using residual gravity data from all benchmarks. While depth is insensitive to the assumed source density change, the radius scales to the inverse of density. Assuming a volume fraction of 30% which is fully permeable, filling this void space with (hydrothermal) fluids of density 1000 kg/m^3 would produce a bulk density increase of 0.3 kg/m^3. The resultant source radius is around 80±20 m. Although the fit to the data is within errors very good (Fig. 3), we find that the positive anomaly in the eastern part of the LCC cannot be satisfyingly modelled. For this area, we conclude on either a local effect or, more likely, an error in the GPS measurements during the installation of benchmark RAJA, since the reported gravity increase results from the free-air effect of the 7±4 cm inflation detected over the 14 months period. Ignoring the potentially erroneous GPS measurement, the gravity residual for RAJA matches those of neighbouring benchmarks MAJU and 3RDB. Combining all available geophysical information, we conclude that migration of hydrothermal fluids along a permeable N-S striking zone is the most likely cause of the observed perturbation of the gravity field. A conceptual model of mass migration covering the 14-month observation period is shown in Fig. 4.

Conclusions

While magma recharge at depth into the north-western rift zone of Tenerife is likely to have triggered the reawakening of the CVC, the cause of the 14 month perturbation of the gravity field is most probably not related to magma flow. A more likely scenario is the migration of fluids inside the complex triggering the observed gravity changes.

We demonstrate that time-lapse microgravity monitoring of active volcanoes can provide vital insights into their sub-surface dynamics, particularly where structural complexities and heterogeneous mechanical properties of the subsurface do not obey a simple linearly elastic relationship of stress generation and resultant ground deformation [*Dvorak and Dzurisin*, 1997]. Arrival of a small batch of magma at depth and the release and upward migration of hot fluids may be a common trigger of reactivation after long repose periods and may be quantifiable by perturbations in the gravity field but may not be accompanied by ground deformation. Quantification of sub-surface mass/density changes must be regarded as essential for the detection of potential pre-eruptive signals at reawakening volcanoes before ground deformation or other geophysical signals become quantifiable [*Rymer*, 1994].

Acknowledgments

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Figure captions:

Figure 1:

Perspective view of Tenerife island located in the Canarian Archipelago off the coast of North-West Africa (inset), using a colour-coded digital elevation model (DEM; elevation in meters). Highest point is Teide volcano (3718 m a.s.l.) located at 28.27°N and 16.60°W. Black dots indicate epicentres of seismic events recorded between May 2004 and July 2005 by the National Geographic Institute [*http://www.ign.es*]. Black rectangle identifies the area covered by the joint GPS/gravity network. LCC indicates the location of the Las Cañadas caldera.

Figure 2:

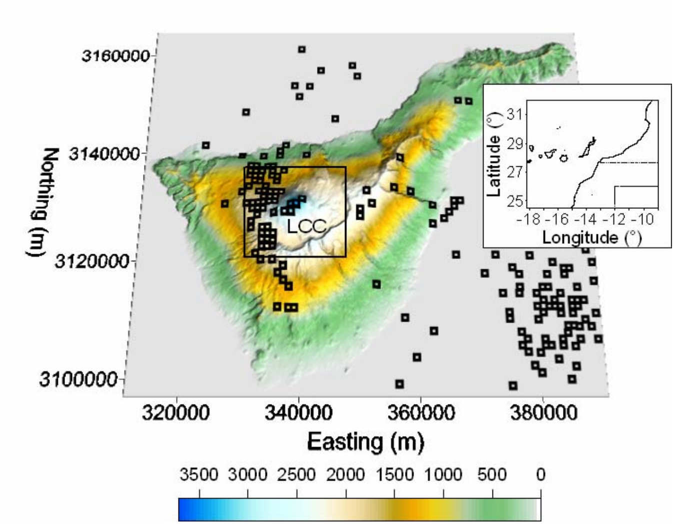
Residual gravity changes between (a) May and July 2004; (b) May 2004 and April 2005; (c) May 2004 and July 2005. (d) is the same as (c), but corrected for the effect of water table changes. Gravity changes are draped over a DEM of the central volcanic complex (CVC) of Tenerife. Black line in (a) delineates head wall of the Las Cañadas caldera (LCC). Benchmark locations (crosses) and identification are shown as well as the prominent topographic features of the Santiago Rift, Teide volcano and the Orotava Valley (OV). Uncertainty in gravity changes are on average ±0.015 mGal (1 mGal= 10μm/s^2). In (c) the area to the east of the CVC, where a gravity decrease was detected, coincides with the intersection of the Las Cañadas caldera with the collapse scar of the Orotava valley. This zone represents a major hydrological outlet of the caldera. In (d) stars represent epicentres of seismic events recorded between May 2004 and July 2005. Both gravity increase and seismicity appear to be spatially and temporally correlated. Line A-B represents datum for profile shown in Fig. 4.

Figure 3:

Predicted (a) and residuals between observed and predicted gravity changes (mGal) (b) for the period May 2004 to July 2005. Predicted values are derived from inversion for an infinite horizontal cylinder as an approximation of the zone undergoing a mass/density increase at the northern and western slopes of the PV-PT complex. Observed gravity changes were corrected for the effect of water table fluctuations in the central and eastern part of the LCC prior to inversion. Red colours indicate that the model is predicting higher gravity changes than observed, blue colours indicate the opposite. Green colours indicate match between predictions and observations.

Figure 4:

Cross-section through the CVC along the profile A-B shown in Figure 2d, including a conceptual model of events between May 2004 and July 2005. (1) Likely injection of magma during peak of onshore seismic activity two weeks before installation of network (May 2004). (2) Release of fluids or perturbation of existing hydrothermal system causing migration of fluids from NW to SE (May - July 2004; Fig. 2a) and later (July 2004-April 2005 and further into July 2005) along a N-S striking zone (Figs. 2b-d). (3) Upward migration of fluids along the upper surface of the high density/low permeability Boca Tauce magmatic body situated beneath the western caldera [*Ablay and Kearey*, 2000]. (4) Fluid migration into an overlying aquifer, located at a depth greater than 900 m beneath the LCC floor and thought to feed the PT summit fumaroles [*Araña et al., 2000*], can explain the increased fumarolic activity of Teide in 2004. The western caldera boundary fault may act as a pathway for fluids to shallower depth.


3160000
3140000
3120000
3100000
Northing (m)
320000
340000
360000
380000
Easting (m)
LCC
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31
29
27
25
Latitude (°)
−18 −16 −14 −12 −10
Longitude (°)

FIGURE 1

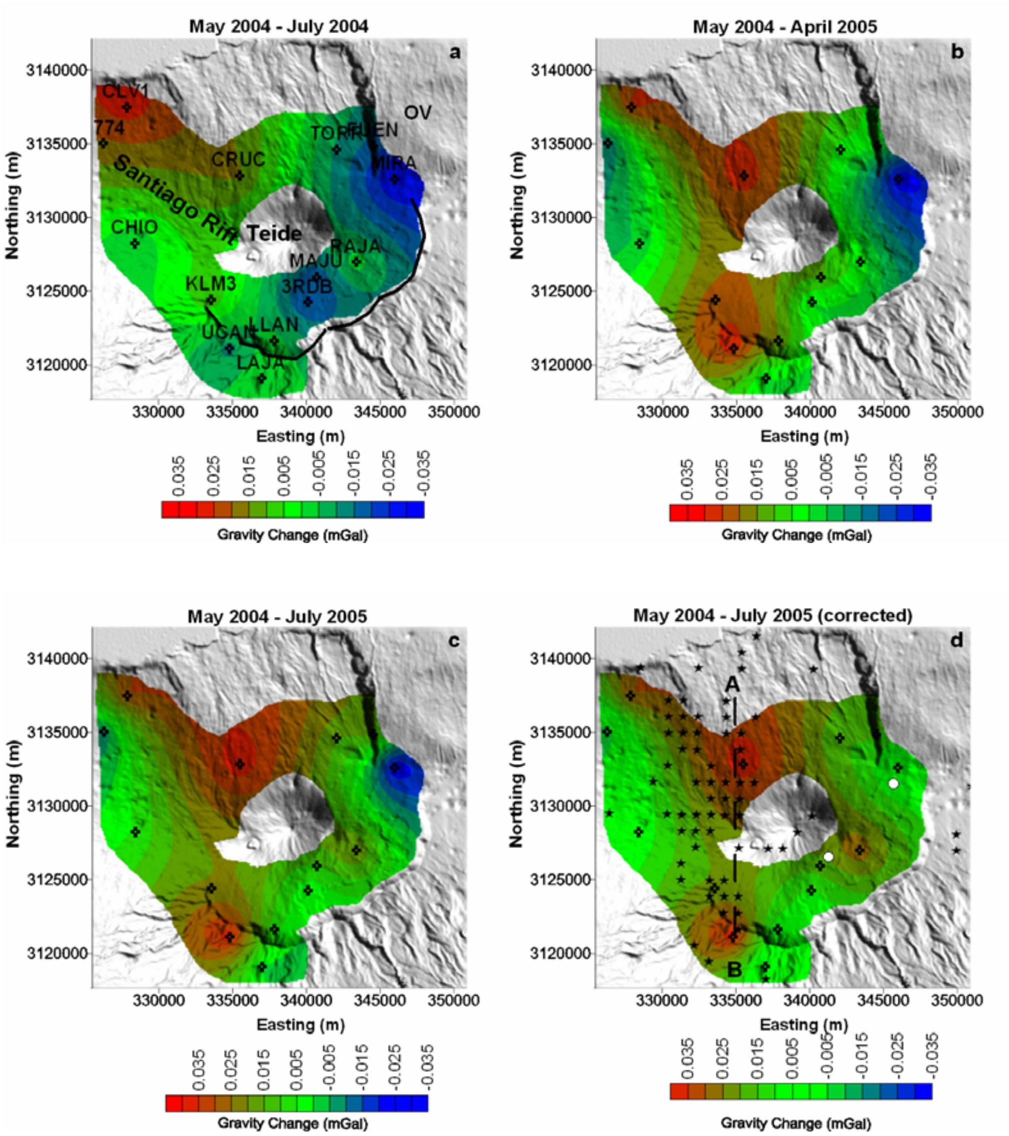
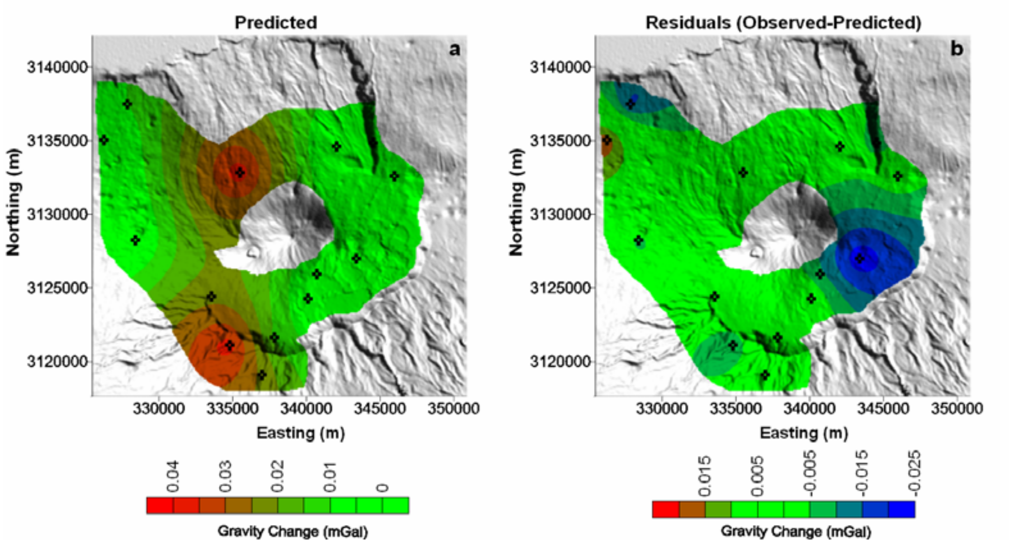

May 2004 - July 2004
a
CLV1
774
OV
TORR
FUEN
MIRA
CRUC
Santiago Rift
Teide
CHIO
RAJA
MAJU
3RDB
KLM3
UCAN
LLAN
LAJA
May 2004 - April 2005
b
May 2004 - July 2005
c
May 2004 - July 2005 (corrected)
d
A
B
Northing (m)
Easting (m)
3140000
3135000
3130000
3125000
3120000
330000
335000
340000
345000
350000
0.035
0.025
0.015
0.005
-0.005
-0.015
-0.025
-0.035
Gravity Change (mGal)

FIGURE 2


Predicted
Residuals (Observed-Predicted)
a
b
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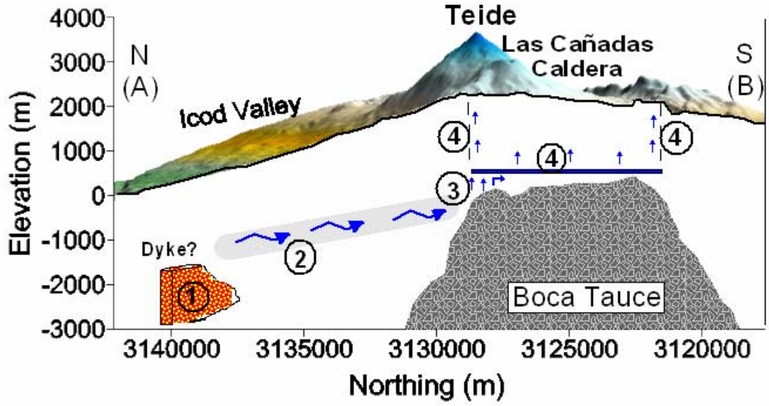
3135000
3130000
3125000
3120000
Northing (m)
330000
335000
340000
345000
350000
Easting (m)
0.04
0.03
0.02
0.01
0
0.015
0.005
-0.005
-0.015
-0.025
Gravity Change (mGal)

FIGURE 3



350

351 **FIGURE 4**